A search for neutrino bursts in the Galaxy with the Baksan Underground Scintillation Telescope; 38 years of exposure

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Abstract The experiment on recording neutrino bursts has been carried out since the mid-1980. As the target, we use two parts of the facility with the total mass of 242 tons. Over the period from June 30, 1980 to December 31, 2018, the actual observational time is 33.02 years. No candidate for the stellar core collapse has been detected during the observation period. An upper bound of the mean frequency of core collapse supernovae in our Galaxy is 0.070 year^{-1} (90% CL).

Keywords: Neutrino, Supernova

1. Introduction

Core-collapse supernovae are among the most powerful sources of neutrinos in the Universe. Recording the supernova SN 1987A has made a considerable impact on both theoretical investigation of SN phenomenon and experimental facilities development. The detection of neutrinos from the supernova SN1987A experimentally proved the crucial role of neutrinos in the explosion of massive stars, as was suggested more than 50 years ago [1, 2, 3].

Due to their high penetration power, neutrinos deliver information on physical conditions in the core of the star during the gravitational collapse. SN1987A has become the nearest supernova in the past several hundred years, which allowed the SN formation process to be observed in unprecedented detail beginning with the earliest time of radiation. It was the first time that a possibility arose for comparing the main parameters of the existing theory - total radiated energy, neutrino temperature, and neutrino burst duration - with the experimentally measured values [4, 5].

The SN1987A event has demonstrated significant deviations from spherical symmetry. It means the SN phenomenon is substantially multidimensional process. In recent years great progress has been achieved in two-dimensional (2D) and three-dimensional (3D) computer simulations of an SN explosion. 3D simulations of the evolution of massive stars at the final stage of their life (SN progenitors) have revealed very important role of non-radial effects. However, further analysis would be mandatory when high-resolution 3D-simulations will become available.

Since light (and electromagnetic radiation in general) can be partially or completely absorbed by dust in the galactic plane, the most appropriate tool for finding supernovae with core collapse are large neutrino detectors. In the past decades (since 1980), the search for neutrino bursts was carried out with such detectors as the Baksan Scintillation Telescope[6, 7], Super-Kamiokande [8], MACRO [8], LVD [10], AMANDA [11] and SNO [12]. Over the years, our understanding of how massive stars explode and how the neutrino interacts with hot and dense matter has increased by a tremendous degree. At present the scale and sensitivity of the detectors capable of identifying neutrinos from a Galactic supernova have grown considerably so that current generation detectors [13, 14, 15] are capable of detecting of order ten thousand neutrinos for a supernova at the Galactic Center.

The Baksan Underground Scintillation Telescope (BUST) [16] is the multipurpose detector intended for wide range of investigations in cosmic rays and particle physics. One of the current tasks is the search for neutrino bursts. The facility operates under this program almost continuously since the mid-1980s. The total galaxy observation time amounts to 90% of the calendar time.

The paper is built as follows. Section 2 is a brief description of the facility. Section 3 is dedicated to the method of neutrino burst detection. Conclusion is presented in Section 4.

2. The facility

The Baksan Underground Scintillation Telescope is located in the Northern Caucasus (Russia) in the underground laboratory at the effective depth of 8.5×10^4 g·sm^{-2} (850 m of w.e.) [16]. The facility has dimensions $17 \times 17 \times 11$ m^3 and consists of four horizontal scintillation planes and four vertical ones (Fig. 1).

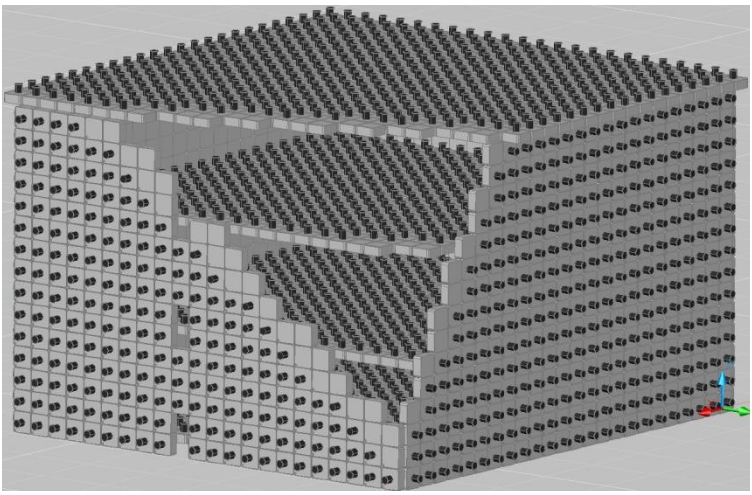

***Fig1**. The Baksan underground scintillation telescope*

The upper horizontal plane has an area of 290 m^2 and consists of 576 (24×24) liquid scintillator counters of the standard type, three lower planes have 400 (20×20) counters each. The vertical planes have 15×24 and 15×22 counters. The horizontal scintillation planes are located on the floors that consist of an 8-mm-thick iron bottom plate, steel beams (the total iron thickness is 2.5 cm or 20 g·cm$^{-2)}$, and a 78-cm-thick fill of low-background rock (dunite) (a concrete cap is at the top). The total thickness of one telescope layer (the scintillator layer plus the floor) is 165 g·cm^{-2}. The vertical walls of the BUST building are also composed of dunite with iron reinforcement. The charge and atomic weight of the nuclei of BUST material atoms averaged over the volume of one facility layer are $\overline{Z}$ = 12.8 and ove $\overline{A}$ = 26.5, respectively. The radiation unit of length for the telescope material is t_0 = 23.5 g·cm^{-2}.

The distance between neighboring horizontal scintillation layers is 3.6 m. The angular resolution of the facility is 2.5^o (if the trajectory length exceeds 8 m), time resolution is 5 ns.

The standard autonomous counter is an aluminum tank 0.7×0.7×0.3 m^3 in size, filled with an organic C_nH_{2n+2} (n ≈ 9) scintillator. The scintillator volume is viewed by one FEU-49 photomultiplier (PM) with a photocathode diameter of 15 cm through a 10-cm-thick organic glass window (the thick window serves to reduce the light collection nonuniformity).

Four signals are taken from each counter. The signal from the PM anode is used to measure the plane trigger time and the energy deposition up to 2.5 GeV (the most probable energy deposition of a muon in a counter is 50 MeV ≡ 1relativistic particle). The anode signals from the counters of each plane are successively summed in three steps: ∑25, ∑100, and ∑400. In addition to the signals from the entire plane, this also allows the signals from its parts to be used. The current output (the signal from the PM anode through an integrating circuit) is used to adjust and control the PM gain. The signal from the 12th dynode is fed to the input of a discriminator (the so-called pulse channel) with a trigger threshold of 8 and 10 MeV for the horizontal and vertical planes, respectively. The signal from the fifth PM dynode is fed to the input of a logarithmic converter, where it is converted into a pulse whose length is proportional to the logarithm of the signal amplitude [17]. The logarithmic channel (LC) allows the energy deposition in an individual counter to be measured in the range 0.5-600 GeV.

The signal from each plane ∑400 is fed to linear coders which have the measurement range of (6 – 80) MeV and the energy resolution 60 KeV. These coders allow us to measure with high accuracy an energy deposition amplitude of single events (see below) which will appear in case of a neutrino burst.

The trigger is an operation of any counter pulse channel of the BUST.

3. The method of neutrino burst detection

The BUST consists of 3184 standard autonomous counters arranged in four horizontal and four vertical planes. The total scintillator mass is 330 t, and the mass enclosed in three lower horizontal layers (1200 standard counters) is 130 tons. The majority of the events recorded with the Baksan telescope from a supernova explosion will be produced in inverse beta decay (IBD) reactions:

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

If the mean antineutrino energy is E_{ν_e}= 12 - 15 MeV [18, 19] the path of e^+ (produced in reaction (1) will be confined, as a rule, in the volume of one counter. In such a case the signal from a supernova explosion will appear as a series of events from singly triggered counters (one and only one counter from 3184 operates; below we call such an event "the single event") during the neutrino burst. The search for a neutrino burst consists in recording of single events cluster within time interval of τ = 20 s (according to the modern collapse models the burst duration does not exceed 20 s).

The expected number of neutrino interactions detected during an interval of duration Δt from the beginning of the collapse can be expressed as:

$$N^{H}_{ev}=N^{H}\int_{0}^{\Delta t}dt\int_{0}^{\infty}dE\times F(E,t)\times\sigma(E)\times\eta(E) \quad (2)$$

here N_H is the number of free protons, F(E,t) is the flux of electron antineutrinos, σ(E) - the IBD cross section, and η(E) is the detection efficiency. The symbol "H" in left side indicates that the hydrogen of scintillator is the target. In calculating (2), we used the Fermi-Dirac spectrum for the $\bar{\nu}_e$ energy spectrum integrated over time (with the antineutrino temperature $k_B T$=3.5 MeV) and the IBD cross section, σ(E), from [20].

For an SN at a "standard" distance of 10 kiloparsecs, a total energy radiated into neutrinos of $\varepsilon_{tot} = 3 \times 10^{53}$ erg, and a target mass of 130 t (the three lower horizontal planes, see Fig. 1), we obtain (we assume the $\bar{\nu}_e$ flux is equal to $1/6\times\varepsilon_{tot}$)

$$N^{H}_{ev} \cong 38 \quad \textit{(no oscillations)} \quad (3)$$

Flavor oscillations are unavoidable of course. However, it was recognized in recent years that the expected neutrino signal depends strongly on the oscillation scenario (see e.g. [21, 22, 23, 24]).

The oscillation effects depend on many unknown or poorly known factors. These are the self-induced flavor conversions, the matter suppression of self-induced effects, specific flavor conversions at the shock-fronts, stochastic matter flows fluctuations. In the absence of a quantitatively reliable prediction of the flavor-dependent fluxes and spectra it is difficult to estimate the oscillation impact on ν_e and $\bar{\nu}_e$ fluxes arriving to the Earth. Therefore, it is an open question how the estimation (3) is changed under the influence of flavor conversions effects.

Background events are 1) radioactivity (mainly from cosmogeneous isotopes) and 2) cosmic ray muons if only one counter from 3184 hit. The total count rate from background events (averaged over the period of 2001 - 2018 years) is f1 = 0.0207 s^{-1} in internal planes (three lower horizontal layers) and ≈ 1.5 s^{-1} in external ones. Therefore three lower horizontal layers are used as a target; below, we will refer to this counter array as the D1 detector (the estimation (3) has been made for the D1 detector).

Background events can imitate the expected signal (k single events within sliding time interval τ with a count rate

$$p(k) = f_1 \times \exp\,(-f_1 \times \tau) \times \frac{(f_1\times\tau)^{k-1}}{(k-1)!} \quad (4)$$

Processing of experimental data (single events over a period 2001 - 2018 y; T_{actual} = 15.5 years) is shown by squares and triangles in Fig. 1 in comparison with the expected distribution according to the expression (4) calculated at $f_1 = 0.0207$ s^{-1}. Note that there is no normalization in Fig. 2.

It should be explained that the sliding time interval moves in discrete steps from one single event to the next, so that at least one event is always present in the cluster (at the beginning of the interval). This gives rise to the coefficient f_1 in the expression (4). If a new single event falls into the τ-sec window when the beginning of the interval passes to the next event, then the number of clusters with a given multiplicity increases by one. If, however, no new event is added and the newly formed cluster has a multiplicity smaller by one than the preceding one, then this cluster is considered to be a “fragment” of the preceding one and is disregarded in the distribution.

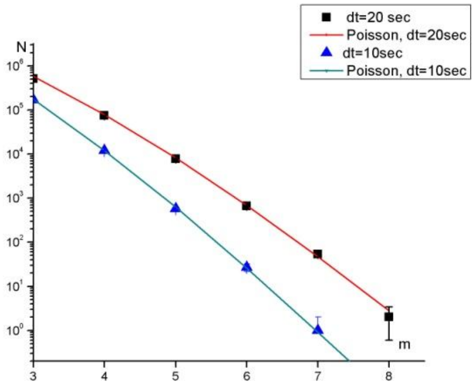

Fig2. *The number of clusters with k single events within time interval dt= 20 s and dt= 10 s. Squares and triangles are experimental data, the curves are the expected number according to the expression (4).*

This variant of processing guarantees against the loss of a cluster with a greater multiplicity (because some of the events fall into the neighboring cluster), but, at the same time, some clusters overlap in time, which leads to some deviation from the Poisson distribution.

According to the expression (4), background events create clusters with k = 8 with the rate 0.178 y^{-1}. The expected number of such clusters during the time interval T = 15.5 y is 2.75 that we observe (2 events). The formation rate of clusters with k = 9 background events is 9.2 ≈ 10^{-3} y^{-1}, therefore the cluster with multiplicity $k \geq k_{th} = 9$ should be considered as a neutrino burst detection.

3.1. Two independent detectors

To increase the number of detected neutrino events and to increase the "sensitivity radius" of the BUST, we use those parts of external scintillator layers that have relatively low count rate of background events. The total number of counters in these parts is 1030, the scintillator mass is 112 tons. We call this array the D2 detector, it has the count rate of single events f_2 = 0.12 s^{-1}. The joint use of the D1 and the D2 detectors allows us to increase the number of detected neutrino events and the detection reliability of a neutrino burst.

We use the following algorithm: in case of cluster detection with k1 ≥ 6 in the D1, we check the number of single events k2 in the 10-second time frame in the D2 detector. The start of the frame coincides with the start of the cluster in D1. Mass ratio of D2 and D1 detectors 1030/1200 = 0.858 implies that for the mean value of neutrino events k1 = 6 in D1, the mean number of neutrino events in D2 will be $\overline{k2}$times 0.858 *0.8 = 4.12 (factor 0.8 takes into account that the frame duration in the D2 is 10 seconds instead of 20 seconds in the D1). Since the background adds f_2 ×10 s = 1.2 events, we obtain finally $\overline{k2}(\overline{k1}$=6) = 4.12+1.2 = 5.32.

According to the exp. (2), the expected average number of detected neutrino events in the D2 detector is $N_{ev}^{H} \cong 29$ (under the same conditions and assumptions as in (3). So the expected total number of detected neutrino events (in IBD reactions (1)) is

$$N_{ev}^{H} = N_{ev}^{H}(D1) + N_{ev}^{H}(D2) \approx 67 \quad \textit{(no oscillations)} \tag{5}$$

The D1 and the D2 detectors are independent therefore the imitation probability of clusters with multiplicities k1 in the D1 and k2 in the D2 by background events is the product of appropriate probabilities

$$P(k1,k2) = P1(k1) \times P2(k2) \tag{6}$$

and we obtain P(6,5) = 0.23 y^{-1}, P(6,6) = 0.045 y^{-1} (note that P1 is determined according to the expression (4) and P2 is the Poisson distribution).

Therefore the events with k1≥ 6, k2≥6 should be considered as candidates for a neutrino burst detection (since mean values of k1 and k2 are significantly exceeded in two independent detectors simultaneously and the imitation probability of such events by background is very small).

Notice that in case of a real neutrino burst, the remainder of counters (which do not belong to the D1 and the D2) can be used as the third independent detector – the D3 with the mass of 100 ton.

3. Conclusion

The Baksan Underground Scintillation Telescope operates under the program of search for neutrino bursts since June 30, 1980. As the target, we use two parts of the BUST (the D1 and D2 detectors) with the total mass of 242 tons. The estimation (5) allows us to expect ≈ 10 neutrino interactions from a most distant SN (≈ 25 kpc) of our Galaxy.

Background events are 1) decays of cosmogeneous isotopes (which are produced in inelastic interaction of muons with the scintillator carbon and nuclei of surrounding matter) and 2) cosmic ray muons if only one counter from 3184 hit.

Over the period of June 30, 1980 to December 31, 2018, the actual observation time was 33.02 years. This is the longest observation time of our Galaxy with neutrino at the same facility. No candidate for the core collapse has been detected during the observation period. This leads to an upper bound of the mean frequency of gravitational collapses in the Galaxy

$$f_{col} < 0.070 \ y^{-1}$$

at 90% CL. Recent estimations of the Galactic core-collapse SN rate give roughly the value ≈ 2-5 events per century (see e.g. [25].

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